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Relative backscattering yields for electrons and positrons from tungsten at keV energies

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Abstract : The backscattering coefficients (η_0^-, η_0^+) and their ratios for impact of 8-28 keV electrons and positrons with a thick tungsten target at normal incidence, have been determined and compared with the available data on W and Au targets. It is found that the backscattering ratios attain a constant value of about 1.35 at higher impact energies while they are seen to rise significantly at the lower impact energies. The measurements of backscattering yields at three different scattering angles, namely, at $\theta = 110°$, 120° and 130° for normal incidence of 8 keV electrons with a thick tungsten target, have been made. The measured relative yields are studied as a function of θ and they are compared with the available data from other workers. The compared data are found to be in good agreement with each other and to follow a well known Lambert's cosine-law within the experimental uncertainty of measurements.

Keywords : Backscattering yields, stopping power, scattering cross section, electron/positron impact.

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1. Introduction

When a charged particle beam collides with a solid target, some particles of the beam after a number of elastic and inelastic collisions with the atoms of the target, return back and emerge from the surface, while others are transmitted and emerge from the other side of the sample. The remaining particles are trapped into the target. The fractions of trapped, backscattered and transmitted particles depend on the nature and the thickness of the target. For bulk targets, the fraction of backscattered particles reaches its saturation value; generally called backscattering coefficient 'η'. The backscattering coefficient generally depends on the type of incident particles, their primary energy, the target mean atomic number and on the incidence angle. What can be hidden in the simplicity is the extent of the physical interaction between projectile and target. It is clear that the backscattering process must be sensitively determined by the details of the elastic scattering interaction, but it is not clear to what extent, the inelastic process determines the properties of the returning projectiles. Even less is known about the interaction volume for the process. How deep does the typical positron or electron penetrate before returning to the surface? how much of the target material is traversed in the process? how many 'collisions' contribute to the average backscattered particles and what differences, if any, can be expected when matter (electron) and anti-matter (positron) projectiles are interchanged ?. The interaction of slow charged particles, such as, electrons and positrons with solid targets is of prime importance in many areas of surface science, solid state physics and microelectronics [1–11]. The problem, which is not new, has received recent attention because of its importance in electron spectroscopy, electron micro-lithography, positron annihilation spectroscopy and so on [8–15]. Indeed, backscattered electrons from solid targets are utilized to obtain the backscattered electron image in scanning electron microscopy (SEM) and to detect registration

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marks in electron beam lithography [16], while positrons have been used in many ways as a probe to investigate surfaces or thin films of materials [17–19]. There may be a possibility of using the positron beams as industrial analysis tools [11]. Of more fundamental scientific importance, the combined study of electron and positron backscattering provides a rare opportunity to establish detailed interaction cross sections, since it is the simplest matter – antimatter system that can be routinely obtained and controlled in a modest laboratory [20]. In fact, an understanding of positron collision processes in solids underpins and strengthens the description of equivalent electron process, which governs the interpretation of an array of techniques using mono-energetic electrons as a probe of solid samples [21]. In a collision event with an atomic electron or a nucleus, the incident positron loses energy and changes its direction. Atomic electron excitation or ejection affects the energy dissipation of the incident positron and only slightly its direction in the solid, while nuclear collisions are nearly elastic and deflect the incident positron without a relevant energy transfer, due to the large mass difference between the incident particle and the nucleus. Actually, a positron can lose a large fraction of its energy in a single collision (or even be annihilated). Nevertheless, the so-called continuous slowing down approximation is generally accepted; in such an approximation, the positron is assumed to continuously deplete out its energy during its travel inside the solid. In this approach, the relevant function to describe inelastic events is the so-called stopping power, namely the mean energy loss per unit path length in the solid target. It seems then reasonable to conclude that electrons have a probability of backscattering larger than positrons, in agreement with the experimental work of Baker and Coleman [22] and Massoumi *et al* [23,24]. The knowledge of the collision processes can be encapsulated in scattering cross sections that can be used to find either the electron or positron trajectories in a Monte-Carlo simulation [13–16,20–21,25–34] or to obtain stopping powers and transport cross sections needed for analytic transport theory [6, 35]. Backscattering coefficients at normal incidence for electrons (η_0^-) or for positrons (η_0^+) impinging on solid targets may provide stringent tests on the accuracy of the description of a scattering process. Calculations of electron- and positron backscattering coefficients as a function of both incidence angle α and target atomic number Z for a large range of impact energy, have been made by several workers [6,14,20,21,24,26,29–31,33,34,36]. More general theoretical problems of calculating transmission, backscattering and absorption of electrons impinging on supported and unsupported thin films, have also been reported [32,37–39].

Since there are no sufficient data available on backscattering yields for electrons and positrons in the literature at high impact energy for high Z target materials, it was considered worthwhile to investigate the relative strengths and features of these yields from a thick tungsten target at normal incidence in the energy range of 8–28 keV. The dependence of the backscattering coefficients for electrons and positrons and their ratios (η_0^- / η_0^+) on both the incidence angle and the target atomic number have been studied. For comparison, the calculated values are obtained using an expression given by Massoumi *et al* [24]. Our results for η_0^- and (η_0^- / η_0^+) have been compared with those of other workers for W (Z = 74) and Au (Z = 79) targets in the impact energy range of 8–35 keV. The relevant data are compiled and presented in Table 1. The angular data for electrons in the present studies have been integrated to yield the total absolute backscattering coefficients, which are compared with the corresponding values for positrons. The angular measurements, in fact, represent the double differential backscattering yields for mono-energetic incident electrons, *i.e.* $d^2\eta/dEd\theta$ in our investigations, where E is the energy of backscattered electrons.

2. Experimental details

Measurements were carried out on a recently developed experimental set up, the details of which are given and discussed in our previous papers [40–42]. Briefly, a mono-energetic beam of electrons was derived from a custom built electron gun (M/s P.Staib GmbH, Germany) which provided a focused beam of electrons with a 3 mm spot size on the target (20 mm × 14 mm × 0.5 mm) situated at about 500 mm away from the gun. The accuracy of positioning the beam spot on the target was estimated to be about ±1 mm. During the measurements, the incident beam current was kept at about 10 nA. The base pressure of the scattering chamber was maintained at better than 1.6 × 10^{-6} Torr. The chamber is equipped with a movable target holder in the vertical plane at its center to position the target in front of the beam. A high purity thick (0.5 mm) tungsten target (99.90%) was mounted on the target holder. The backscattered electrons emitted from the beam-target interaction zone were accepted within a narrow solid angle ($d\Omega$ = 1.23 Sr) by a 45° parallel plate electrostatic analyzer

Table 1. Backscattering coefficients for impact of electrons (η_0^-), positrons (η_0^+), and the ratio (η_0^-/η_0^+) in the energy range of 8–35 keV at normal incidence for W and Au thick targets.

S.N.	E_p (keV)	η_0^- our experiment 'W' [41]	η_0^- Hunger Kuchler 'W' [43]	η_0^+ Coleman 'W' [22]	η_0^+ Makinen *et al* 'Au' [44]	η_0^+ Monte-Carlo 'Au' [44]	η_0^+ Massoumi *et al* [24]	η_0^-/η_0^+ Coleman *et al*'s η_0^+ normalizes		η_0^-/η_0^+ Makinen et al's η_0^+ normalizes		η_0^-/η_0^+ Monte-Carlo calc. η_0^+ normalizes		η_0^-/η_0^+ Massoumi η_0^+ normalizes		η_0^-/η_0^+ Eqs. (1) and (2)
								our e^- data	Hunger Kuchler e^- data	our e^- data	Hunger Kuchler e^- data	our e^- data	Hunger Kuchler e^- data	our e^- data	Hunger Kuchler e^- data	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)
1	8	0.388	0.475	0.245	0.308	-	-	1.5841	1.9387	1.261	1.5422	-	-	-	-	-
2	10	0.390	0.460	0.260	0.348	-	-	1.500	1 769	1.121	1.3281	-	-	-	-	-
3	12	0.410	-	-	0.372	-	-	-	-	1.102	-	-	-	-	-	-
4	14	0.411	-	-	0.364	-	-	-	-	1.129	-	-	-	-	-	-
5	16	0.413	0.467	0.265	0.372	-	-	1.558	1 7623	1.110	1.2421	-	-	-	-	-
6	18	0.414	-	-	0.3744	-	-	-	-	1.107	-	-	-	-	-	-
7	20	0.421	0.469	0.29	0.3776	-	-	1.525	1.6172	1.114	-	-	-	-	-	-
8	22	0.433	-	-	0.380	-	-	-	-	1 139	-	-	-	-	-	-
9	24	0.443	-	0.285	0.382	-	-	1.554	-	1.160	-	-	-	-	-	-
10	26	0.449	-	-	0 388	-	-	-	-	1.157	-	-	-	-	-	-
11	28	0 450	-	0.30	0.376	-	-	1.500	-	1.177	-	-	-	-	-	-
12	30	-	0.478	-	-	0.385	-	-	-	-	-	1 169	1 416	-	-	-
13	35	-	-	-	-	-	0.342	-	-	-	-	-	-	1.316	1.398	1.25

(full width at half maximum = 12%) equipped with a channel electron multiplier (CEM), which was operated in a pulse counting mode. The electron analyzer could be placed at a chosen angle with respect to the incident beam direction. The electron signals generated by the detector were amplified, shaped and digitized. Accumulation of the desired energy spectra of the backscattered electrons at a chosen angle of incidence was carried out on a window based multi-channel analyzer (MCA) in a pulse height analysis (PHA) mode. These energy spectra were measured as a function of the angle of incidence α and the scattering angle θ. An elaborate description of signal processing, electronic circuits, data acquisition, and analysis *etc*., has been given in Ref. [40]. The typical energy spectra of backscattered electrons from a tungsten target produced by collision of 8 keV electrons are given in Ref. [42]. The backscattering coefficient η is defined as a ratio of the current produced by the backscattered electrons on the collector plate i_p and the sum of the target current i_t and the plate current i_p, that is, $\eta = i_p/(i_p + i_t)$ The measurements of backscattering coefficients at normal incidence for electrons η_0^- in the impact energy range of 8–28 keV, have been discussed in our earlier paper [41]. The overall uncertainty in the measurements of η_0^- was found to be about ±5%.

3. Results and discussion

The backscattering coefficients η_0^- for tungsten and gold in the impact energy range of 8–35 keV are reported by Hunger and Kuchler [43] and by Yadav *et al* [41]; and for positrons (η_0^+) by Baker and Coleman [22] and for gold by Makinen *et al* [44] and Massoumi *et al* [24]. The results obtained by these workers are summarized in Table 1 wherein columns 3 and 4 represent ours and Hunger Kuchler's electron data, columns 6, 7 and 8 show the positron data of Makinen *et al* [44] and Massoumi *et al* [24] for Au, and W in the impact energy range of 8–35 keV. Columns 9 and 10 represent the ratios (η_0^-/η_0^+) for W when the electron data of ours and those of Hunger Kuchler are normalized with Coleman's positron data measured for 8–28 keV impact. Further, the columns 11 and 12 represent this ratio for ours and Hunger Kuchler's electron data when they are normalized with Makinen *et al*'s positron data. The columns 13 and 14 present the data for (η_0^-/η_0^+) after normalizing ours and Hunger Kuchler's electron data with the Monte-Carlo calculations for positron data for W at 30 keV. Similarly, the columns 15 and 16 present the above ratio when normalized with Massoumi *et al*'s positron data for W at 35 keV. It is seen from Table 1 that the Hunger Kuchler's electron data overestimate our electron data for backscattering coefficients of W at all impact energies (see, columns 3 and 4). The discrepancies observed between these two data have been indicated and discussed in our earlier paper [41]. The η_0^+ data of Baker and Coleman for W (see, column 5) are found to be smaller than η_0^+ data for Au reported by Makinen *et al* [44], noting that η_0^- values are similar for W and Au in the considered impact energy range.

The theoretical expression for calculating η_0^+ at normal incidence [24] is given by

$$\eta_0^+(Z) = e^{-8.59/Z^{1/2}} . \tag{1}$$

Also, the values for η_0^- at keV energies are well described by a similar functional dependence on Z [24] as

$$\eta_0^-(Z) = e^{-6.40/Z^{1/2}} . \tag{2}$$

The single datum shown in column 17 of Table 1 for impact energy of 35 keV of electrons and positrons represents the value of (η_0^-/η_0^+) = 1.25 for tungsten using eqs. (1) and (2). If we compare this ratio at 28 keV, (see, columns 9 and 11), then we find the data in column 11 to be about 8% less than the data in column 9; also, if we compare the same ratio at 20 keV (see, columns 10 and 12), then we find data in column 12 to be about 7.6% less than the data in column 10; at 30 keV (see, columns 13 and 14), the ratio shown in column 13 is found to be about 9.4% less than the value in the column 14. Similarly, the ratios given in columns 9 and 11 at 28 keV and at 30 keV (column 13) when compared with the theoretical value (column 17) at 35 keV, are found to differ from each other by 8.3%, 10.6% and 10.7%, respectively. In literature, there are no sufficient theoretical data available; however, when we compare the ratio (η_0^-/η_0^+) with our data (see, column 11) at 28 keV to the available data from the Monte-Carlo calculations at 30 keV (see, column 13), we see that there is a good agreement between our experiment and these calculations.

Various data listed in Table 1 are also displayed in Figure 1. From this figure, it is seen that the ratio (η_0^-/η_0^+) attains a nearly constant value at the high impact energies E_p. It is also noted that it rises significantly at lower impact energies. From Table 1 and Figure 1, it is noted that the data of Massoumi *et al* [24] yield the ratio of electron and positron backscattering probabilities to be approximately 1.3 for E_p = 35 keV. This finding suggests that the ratio depends very little on the atomic number Z

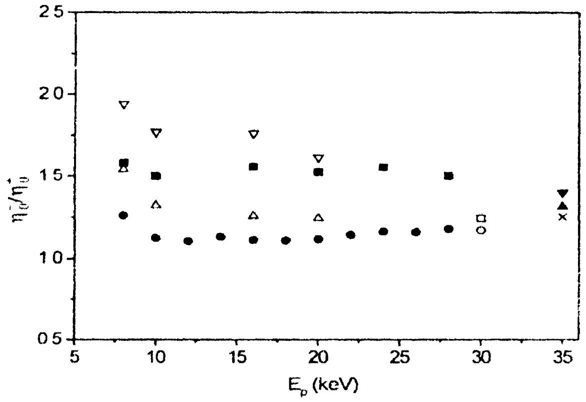

Figure 1. Ratio (η_0^-/η_0^+) for W and Au as a function of the impact energy E_p = 8–35 keV at normal incidence. ∇-Ref [22,43]; ■-Ref [22,41]; Δ-Ref. [43,44]; •-Ref. [41,44], □-Ref [43,44], o-Ref. [41,44] ▼-Ref. [24,43]; ▼-Ref. [41,24]; ×-from eqs. (1) and (2) for 'W'.
Note: Different symbols shown before the given references represent the data for (η_0^-/η_0^+) extracted from the respective references.

of the target or on the incident energy E_p above a few tens of keV (see, Figure 1). From Table 1, we note that the magnitudes of backscattering coefficients for electrons are comparatively higher than for positrons at the same velocity of impact. The difference between the two yields can be understood in terms of their respective elastic scattering cross sections at keV energies. The inelastic scattering cross sections (*i.e.* stopping power) are found to be higher for e^+ than for e^- as discussed earlier.

Figure 2 shows the variation of relative backscattering yields $(d\eta_0^\pm/d\theta)$ as a function of scattering angle θ for e^+[24] and for e^- [24,42] at normal incidence for a thick Au and W targets. Data points shown for electrons at angle θ = 110°, 120° and 130° are from our measurements for 8 keV electrons incident on W at α = 0°. For comparison, our data are normalized with those of Massoumi *et al* [24] at θ = 120°. It is seen that both electron data are in good agreement with each other and follow the well known Lambert's cosine-law *i.e.* $(d\eta_0^\pm/d\theta) \propto \cos\theta$.

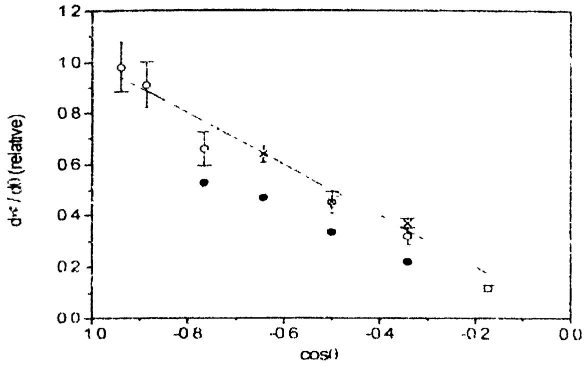

Figure 2. The backscattering coefficient (integrated over energy E) as a function of the scattering angle ($d\eta^*/d\theta$) at normal incidence for impact energy of 8 keV on a thick 'W' target • for positrons Ref [24], o for electrons Ref [24], x for electrons , present measurements

4. Conclusions

The present work discusses and compares the backscattering coefficients for electrons and positrons and their ratios (η_0 / η_0') obtained experimentally and theoretically from different workers for a thick W and Au target under impact of 8–35 keV energies. It is shown that this ratio attains a nearly constant value at higher impact energies whereas it rises significantly at lower energies. In lack of sufficient theoretical data, when we compare (η_0 / η_0') from our electron data at 28 keV for W with that of the Monte-Carlo calculations at 30 keV, we find a good agreement between experiment and theory. Further, our data for backscattering yields (integrated over energy E) at three different scattering angles, namely, $\theta = 110°$, $120°$ and $130°$ for 8 keV electron impact with W at $\alpha = 0°$, not only give a reasonably good agreement with the available data from other workers but also they are found to follow the well known Lambert's cosine-law within the experimental uncertainty of measurements.

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